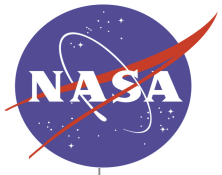

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TPF Coronagraph Architecture

Stuart Shaklan, Luis Marchen, and Joseph Green

October 14, 2003

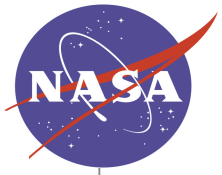
Coronagraph Architecture

My job:
Interpret science requirements, define design parameters and detailed design requirements.
Responsible for Performance Model (Error Budget).
Evaluate performance of various coronagraph and telescope designs.

Science Requirements	Design Parameters	Design Requirements
Inner Working Angle	Telescope Diameter	Wave Front Stability
Bandpass	Telescope Shape	Wave Front Sensing/Control
Source Brightness	Type of Coronagraph	Pointing Accuracy/Stability
Number of Sources	Throughput	Cleanliness/Scatter
Time Constraints		Mask phase/amplitude uniformity.
		Polarization effects.

Architecture Team

Stuart Shaklan, lead
Joseph Green, Coronagraph modeling, SNR, WFS/C
Luis Marchen, Error budget
Larry Scherr, Stray light analysis
Dan Hoppe, Rigorous coronagraph modeling



This Presentation

- Driving Science Requirement
- 'Minimum TPF' Configuration
- Coronagraphs Considered
- Error Budget Modeling
- Inner Working Angle

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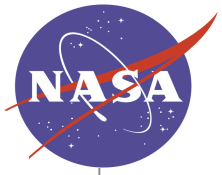

Overarching Science Requirements

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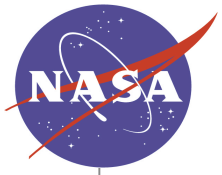
- The science requirements that drive the telescope size and performance are:
  - *Requirement to observe planets at 0.7 AU for a minimum of 30 stars*
  - *Requirement to characterize the planets from 0.5 – 0.8 microns.*
- The Inner Working Angle (IWA) for the 30th closest star of interest requires ~ 80 milli-arcsecond resolution.
- The long-wavelength end of the spectrum drives the telescope diameter (see next page).
- We can choose more or less 'aggressive' coronagraphs to meet the requirement.
- Our ability to meet the requirements determines how aggressive we can be
  - That is, what is the smallest telescope that meets our needs.

- NOTE: The required IWA depends on many factors, including the revisit scenario, sensitivity to planet phase, solar avoidance angle, and of course the list of acceptable stars (e.g. giants? Binaries? Galactic plane?…)



TPF Diameter vs. Resolution Tables

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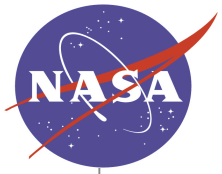
Wavelength (um)	0.5	0.6	0.7	0.8	0.9	1
Length (m)	Distance in mas from center to 3rd minimum					
4	77	93	108	124	139	155
5	62	74	87	99	111	124
6	52	62	72	83	93	103
7	44	53	62	71	80	88
8	39	46	54	62	70	77
10	31	37	43	50	56	62
Length (m)	Distance in mas from center to 4th minimum					
4	103	124	144	165	186	206
5	83	99	116	132	149	165
6	69	83	96	110	124	138
7	59	71	83	94	106	118
8	52	62	72	83	93	103
10	41	50	58	66	74	83
Orbit a (AU)	0.5	1	1.2	1.4	1.6	1.8
Distance (pc)			Star-planet separation (mas)			
10	50	100	120	140	160	180
15	33	67	80	93	107	120
20	25	50	60	70	80	90
25	20	40	48	56	64	72
30	17	33	40	47	53	60



'Minimum' TPF Configuration Point Design

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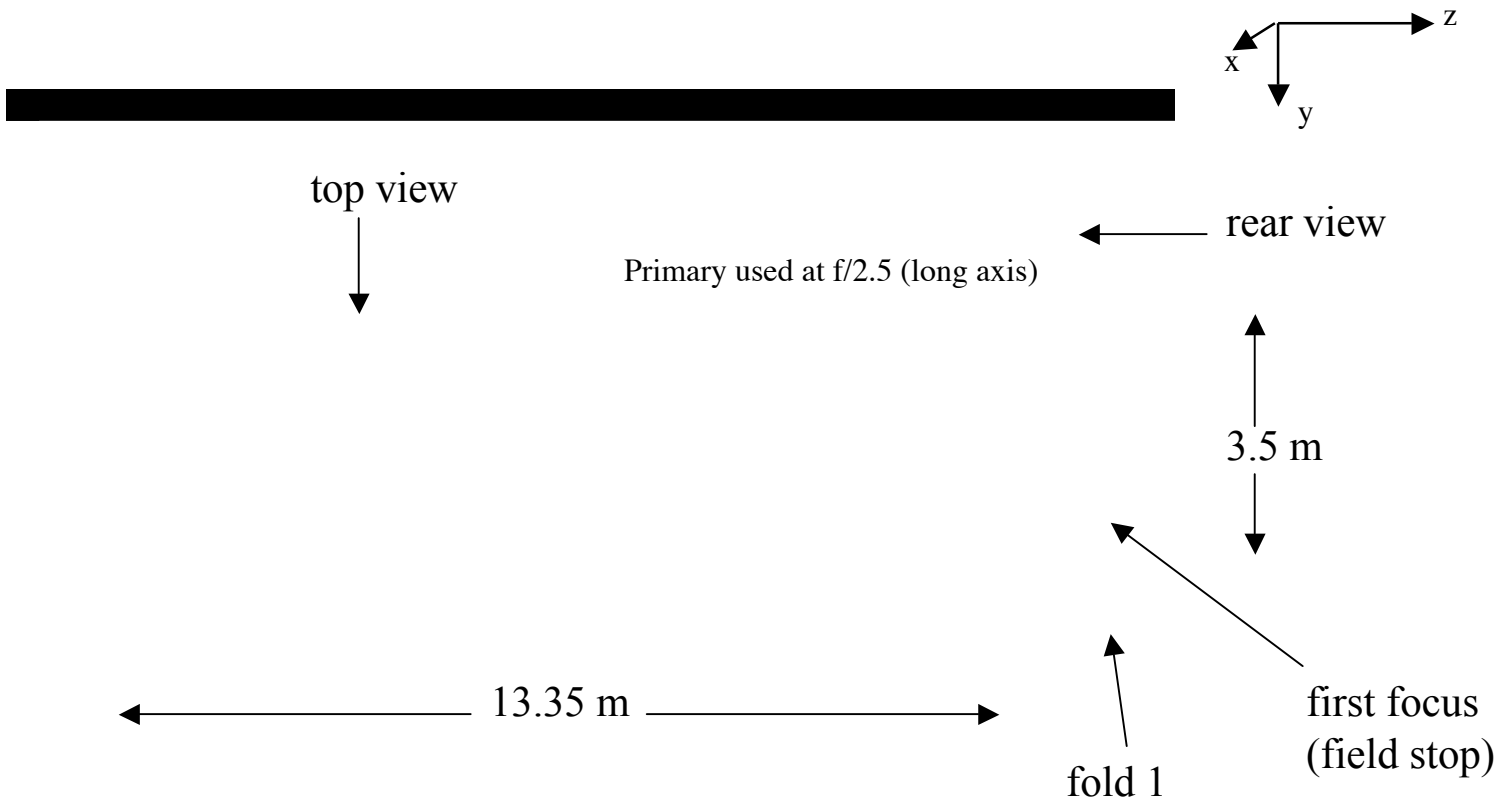
- The starting point for detailed design work was chosen to be:
  - 6 x 3.5 m elliptical aperture working at 3 lambda/D
- 6 m and 3 lambda/D meets the resolution requirement
- 3.5 m is the widest optic we felt we could configure to fit in a Delta-IVH fairing
- Image-plane coronagraph
  - Pupil plane designs do not (yet?) function at 3 lambda/D except over a 1 lambda/D wide search space
- Primary focal length = 11.5 m
- Off-axis Cassegrain, Primary-secondary separation = 10 m

- Other designs considered:
  - longer and shorter versions (P-S separation 7 m and 13.35 m).
  - 8 m long-axis operating at 4 lambda/D
    - Relaxed wave front requirements relative to 3 lambda/D
    - Allows pupil plane masks

'Long' Design



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‘Short’ Design

[redacted]

Similar to Long design, except
-f/# of primary
-7 m vs. 13.35 m primary-secondary separation.

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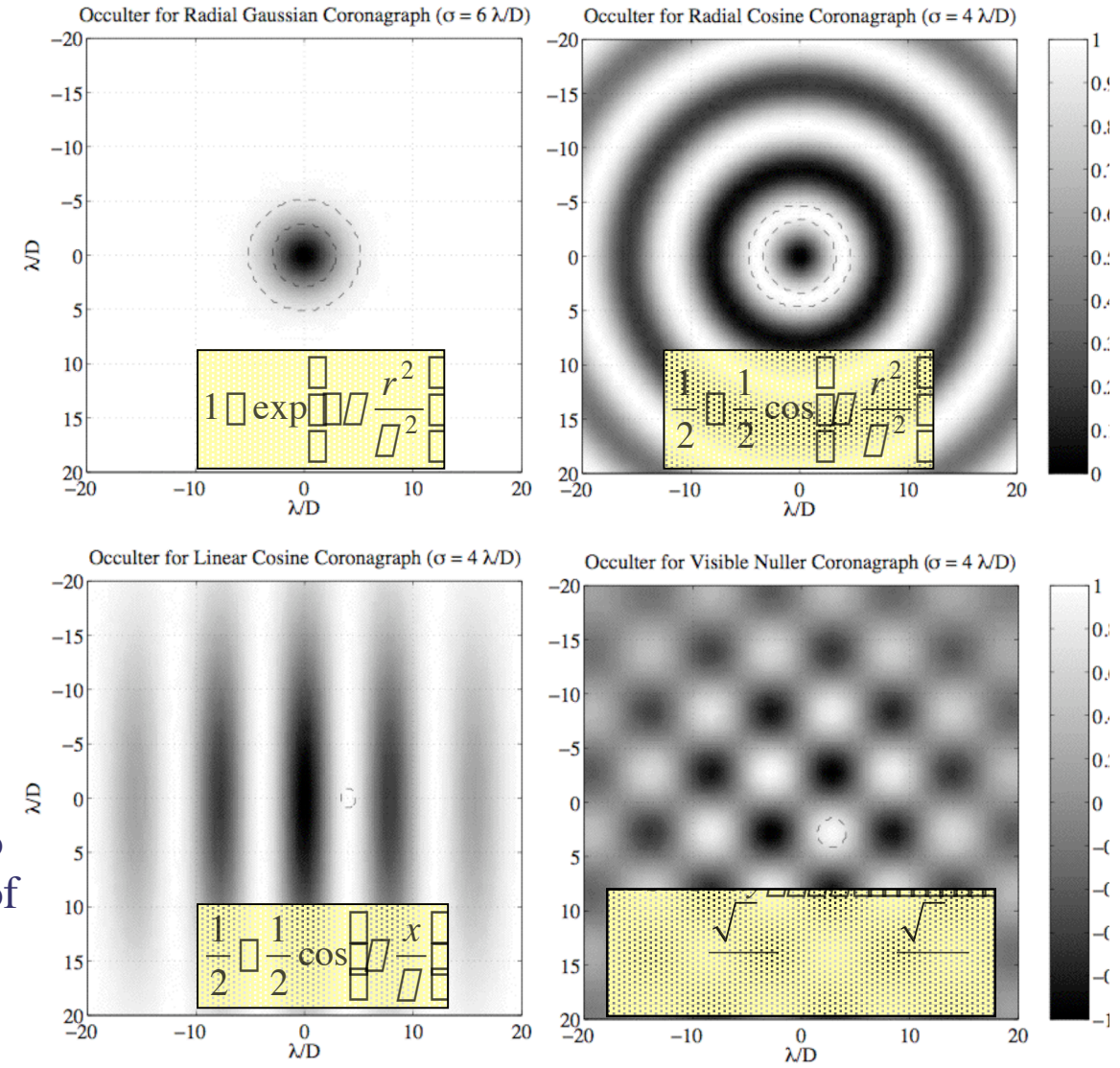
Coronagraphs Under Study

- Occulters considered
  - Radial Gaussian
  - Radial Cosine
  - Linear Cosine
  - sin(x)sin(y)

- The sin(x)sin(y) achieves the same pupil shearing as the *visible-nuller* concept.

- To the 3 sinusoidal occulters we applied a band-limited tapering to limit the spatial extent of the spots



Creating a Stop Using the Field at the Lyot Planes

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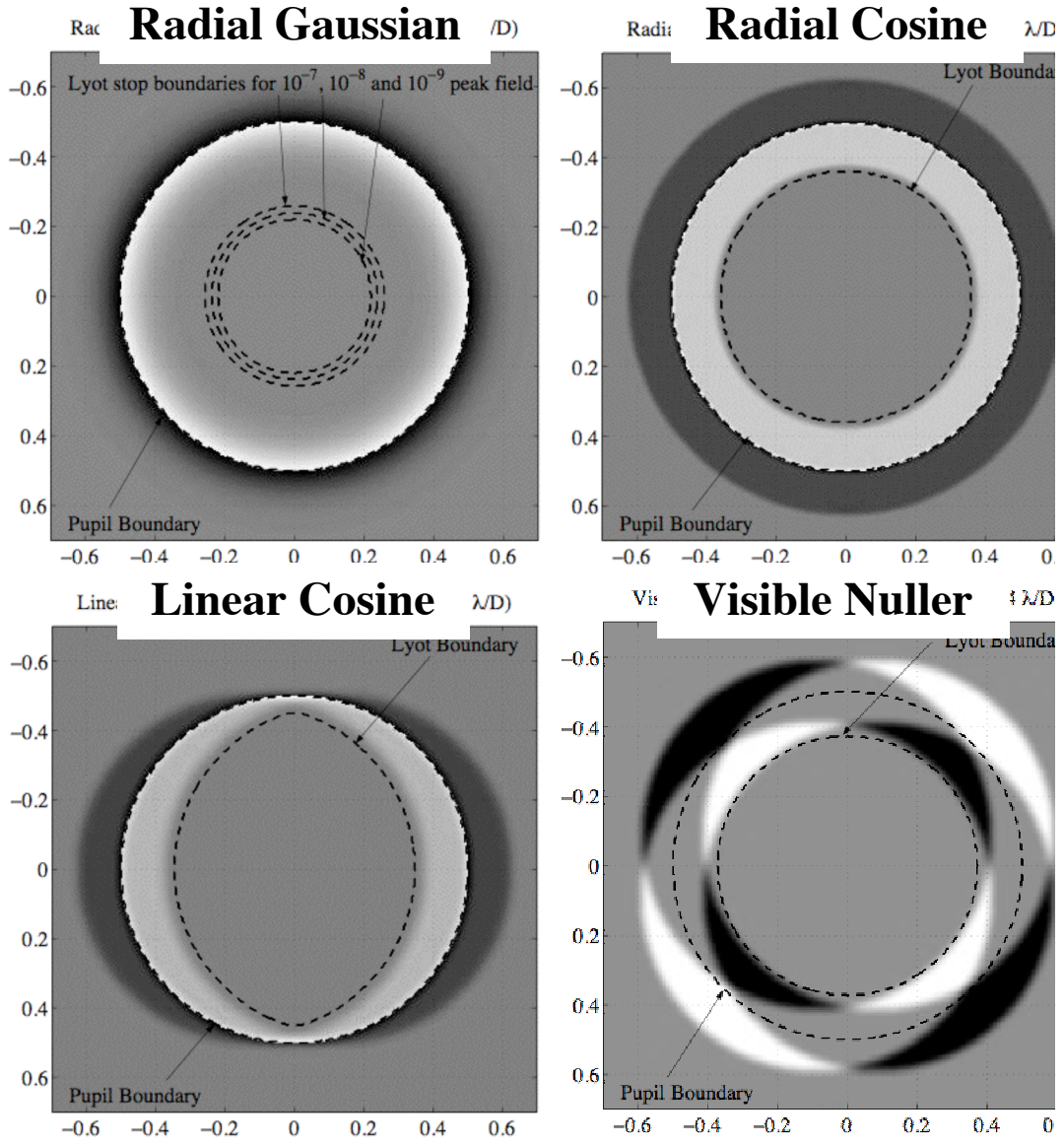
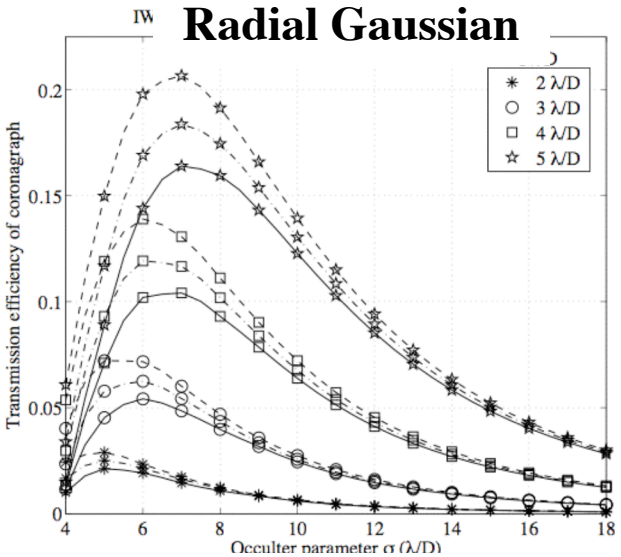
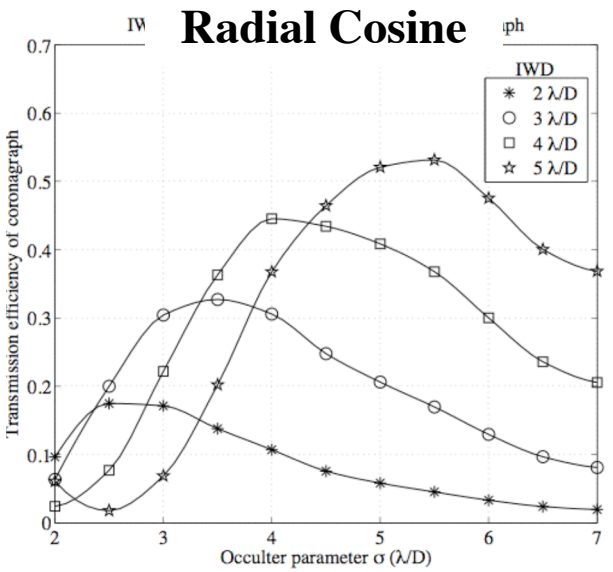
- The Lyot plane is a pupil plane occurring after the occulting stop
- For our study, we setup a Lyot stop design rule by essentially applying a threshold the Lyot field at a given tolerance.
- The tapering we applied to the 3 sinusoidal occulters created a transition region where light leaks into the shearing region.

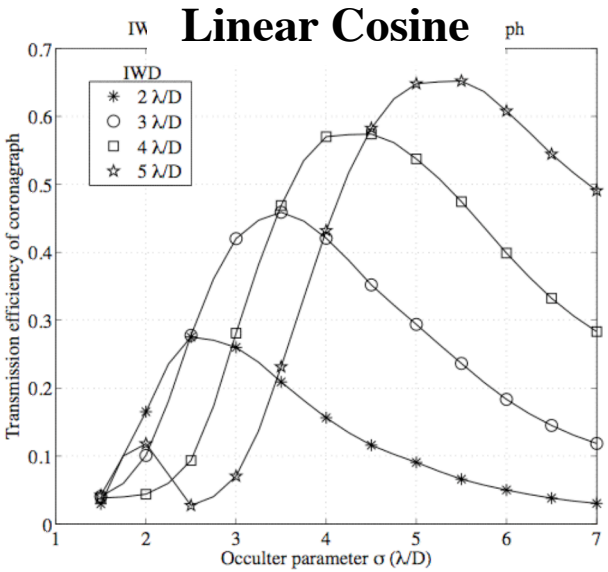


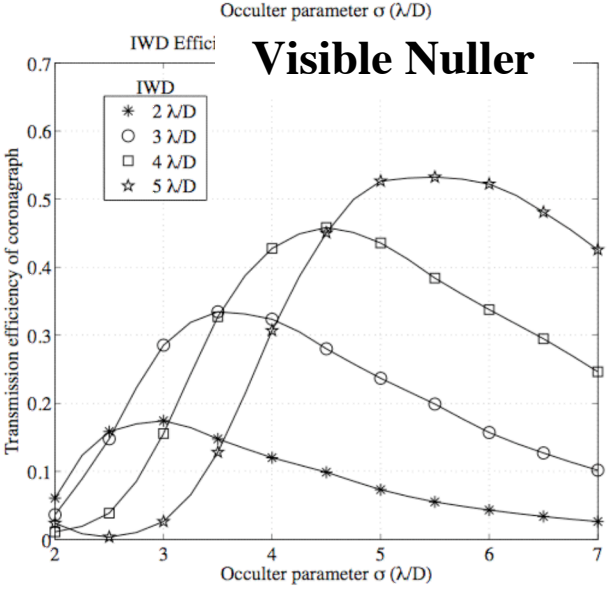
Optimizing Efficiency at a Working Angle

- For the coronagraphs we considered, we find that optimize the efficiency at a working requires the occulting spot to be somewhat *oversized*
- If you the spot was made too big - the increase Lyot stop efficiency does not make up for the attenuation of the occulting mask a particular field angle



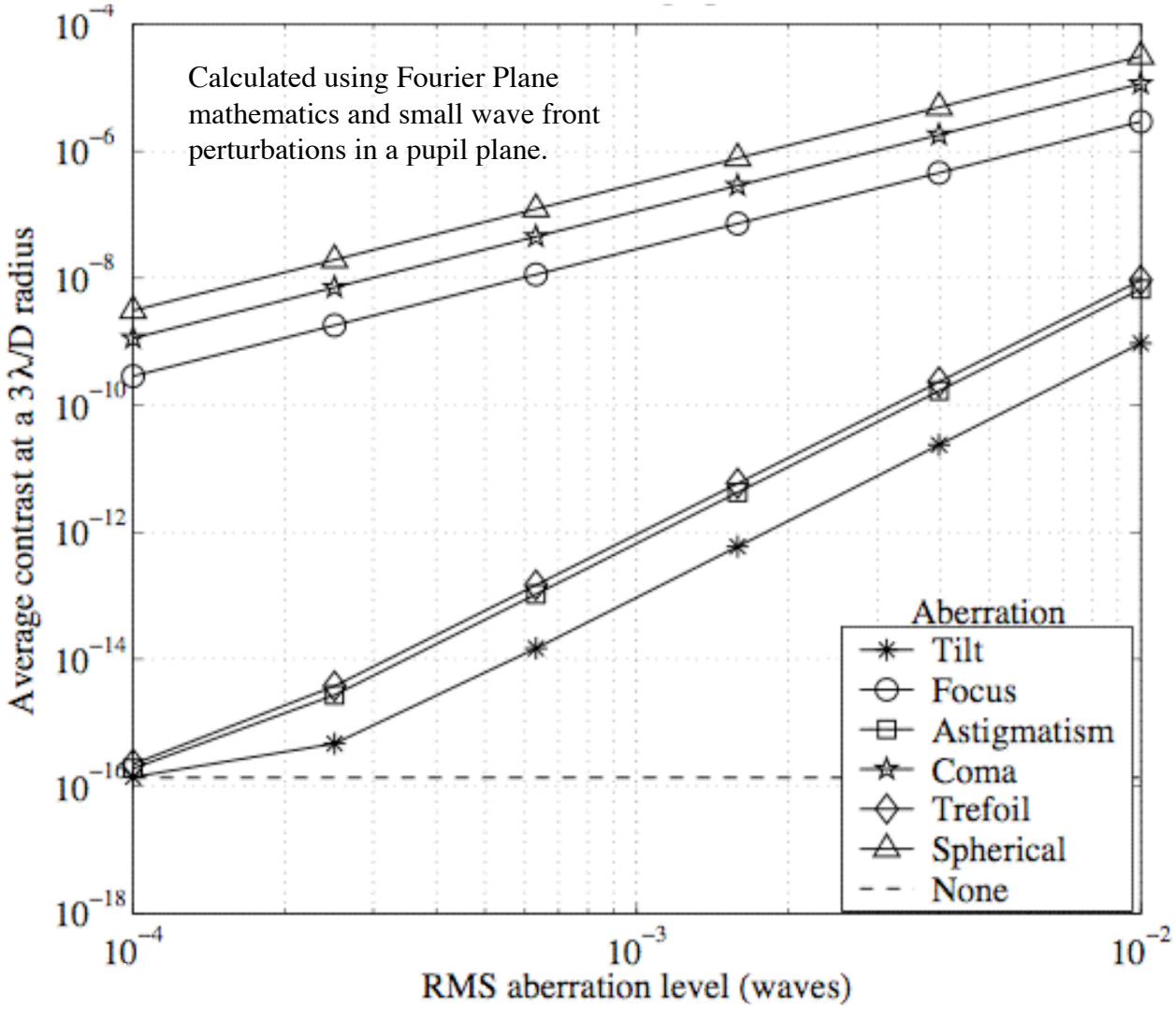






Sensitivity to Low Order Aberrations

Radial Cosine (= 4 /D) Evaluated at 3 /D



- 2nd Order Dependenc
  - Focus, Coma, Spherical

$$C_m \propto \alpha_m \sigma_m^2$$
$$\alpha_m = \partial C_m / \partial \sigma_m^2$$

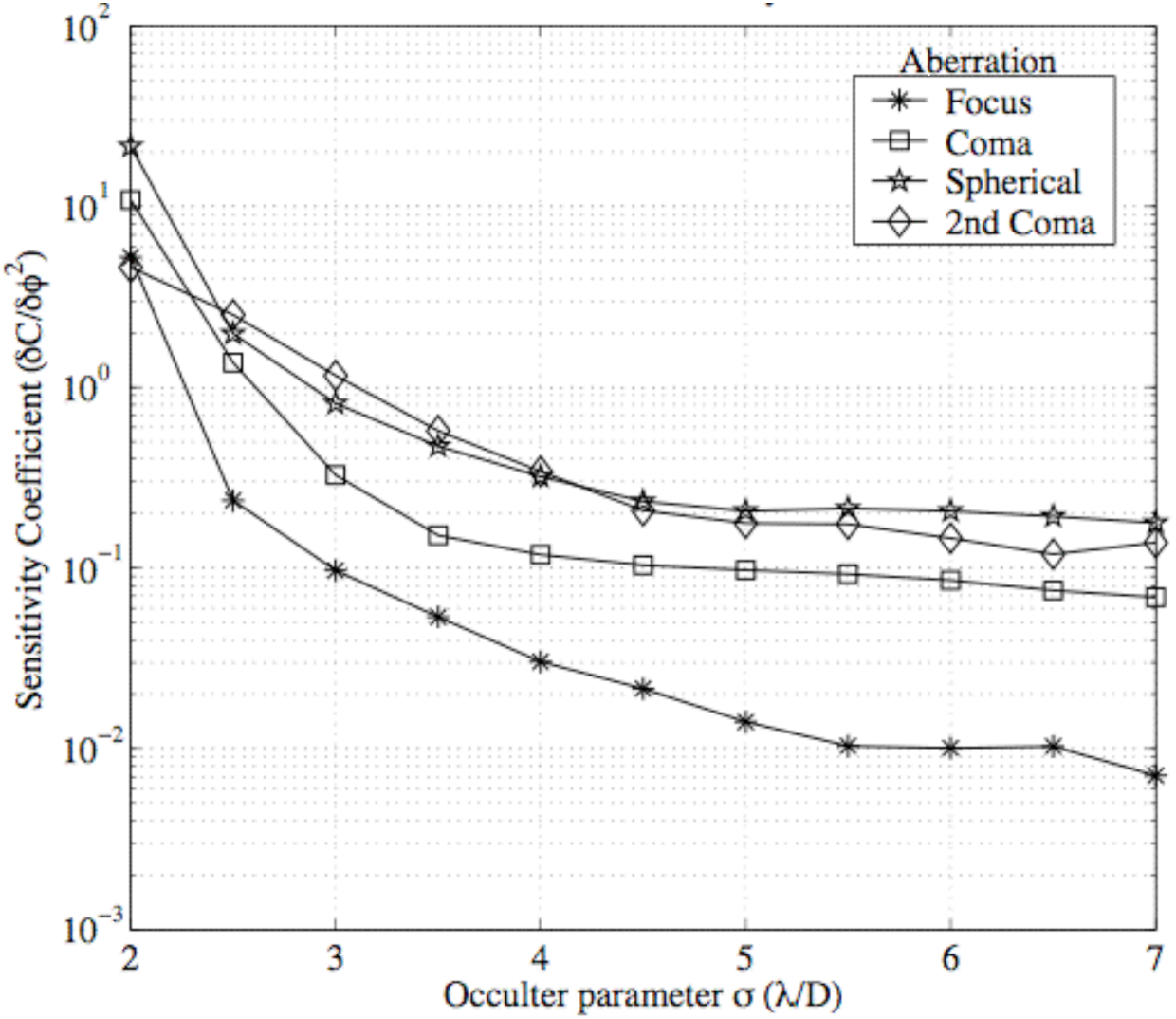
- 4th Order Dependence
  - Tilt, Astigmatism Trefoil

$$C_m \propto \alpha_m \sigma_m^4$$
$$\alpha_m = \partial C_m / \partial \sigma_m^4$$

- Other occulters exhibi different dependencies (e.g.) Visible Nuller 4th order focus sensitivity

Sensitivity □ to the Occulter Size

Radial Cosine Evaluated at 3 □/D



- Shown are the coefficients for the aberrations having a 2nd order dependence

$$\square_m = \partial C_m / \partial \square_m^2$$

- As the occulter size *increases*, blocks more of the scattered light from the low-order modes - *decreasing* their impact upon contrast

Optimizing the Operation of Design Points (Linear Process)

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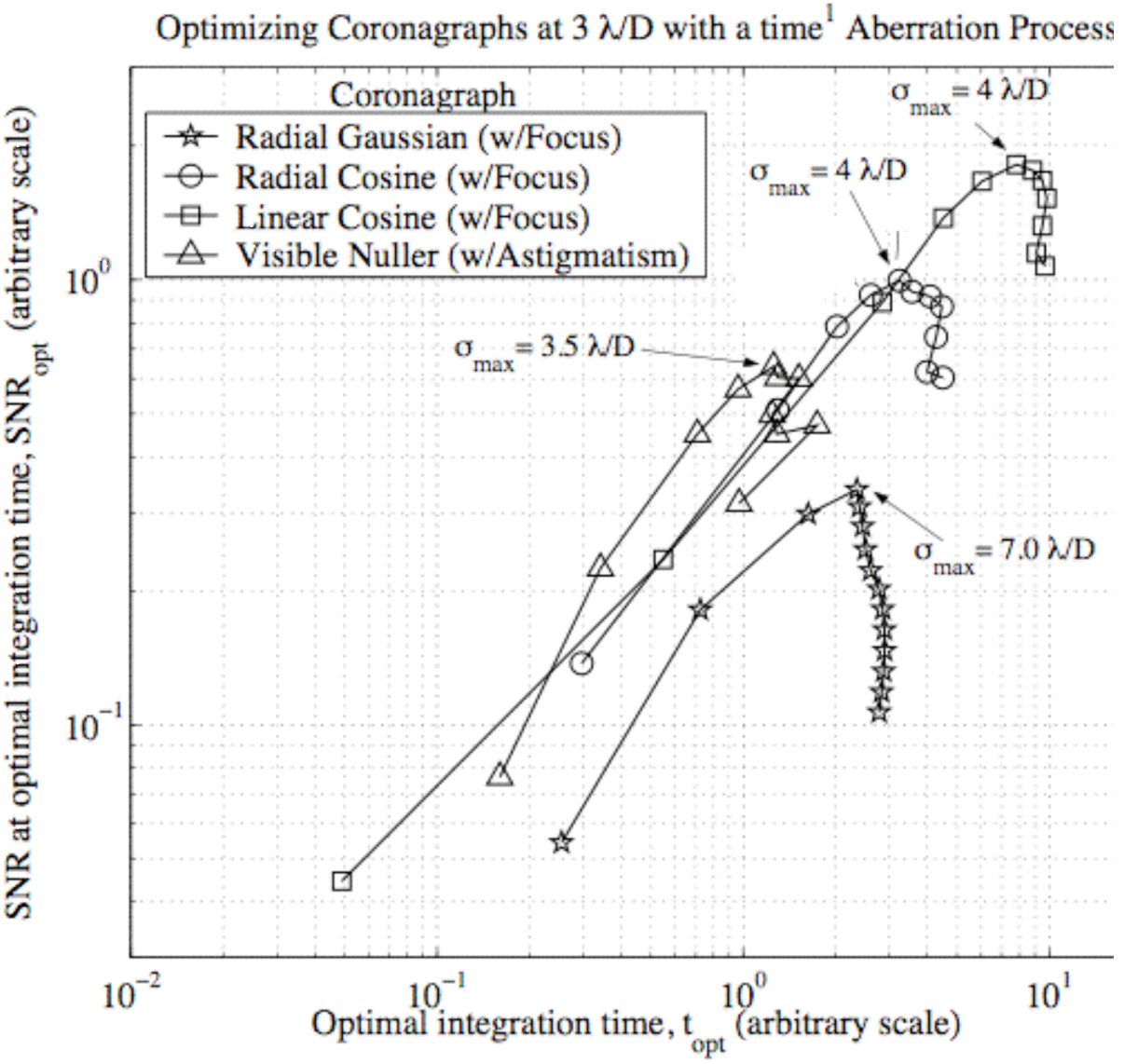
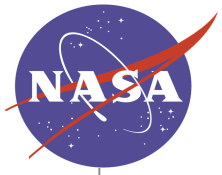
- For any coronagraph design this is an optimum uninterrupted integrate time which maximizes the achievable SNR at a working angle
- As grows from left-to right on the curves, t_{opt} and SNR_{opt} increase
- Eventually the efficiency of the coronagraph overwhelms the diminishing sensitivity making too large an occulter a losing proposition

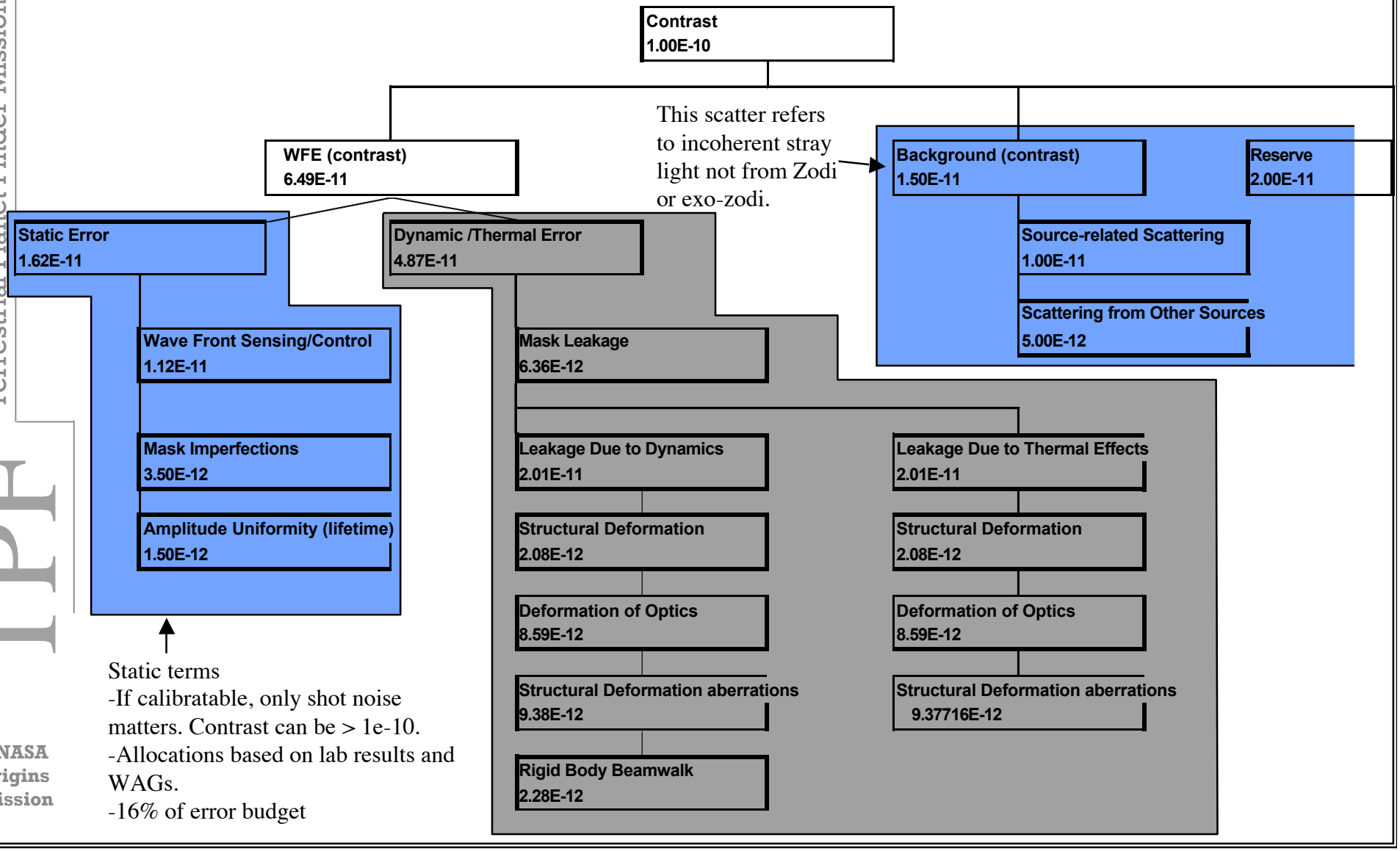




Error Budget Approach

- Simplifying Assumptions
  - DM is set and forget, leading to Static Wave Front Budget
  - No calibration of dynamic/thermal wave front changes
  - Stare mode: no dither, no roll, no background subtraction
  - Speckles look like planets, no chromatic smearing
  - Near field diffraction effects are ignored (DM can correct much of this)
  - Errors are uncorrelated. Contrast contributions add linearly.
- Compute contrast at various points in image plane
  - Budget does not use r.m.s. wave front error
  - Power Spectral Density combined with beam walk gives scatter energy vs. field angle
  - Modeling of low-order wave front errors (e.g. first 16 Zernike modes) gives scatter energy vs. field angle
  - MACOS-generated senstivity matricies determine beam walk and Zernike amplitudes for the 6 x n DOFs (n=number of optical elements)
  - Assume all DOFs are uncorrelated.

TPF Coronagraph Error Tree: 3??D



This scatter refers to incoherent stray light not from Zodi or exo-zodi.

Static terms
-If calibratable, only shot noise matters. Contrast can be > 1e-10.
-Allocations based on lab results and WAGs.
-16% of error budget

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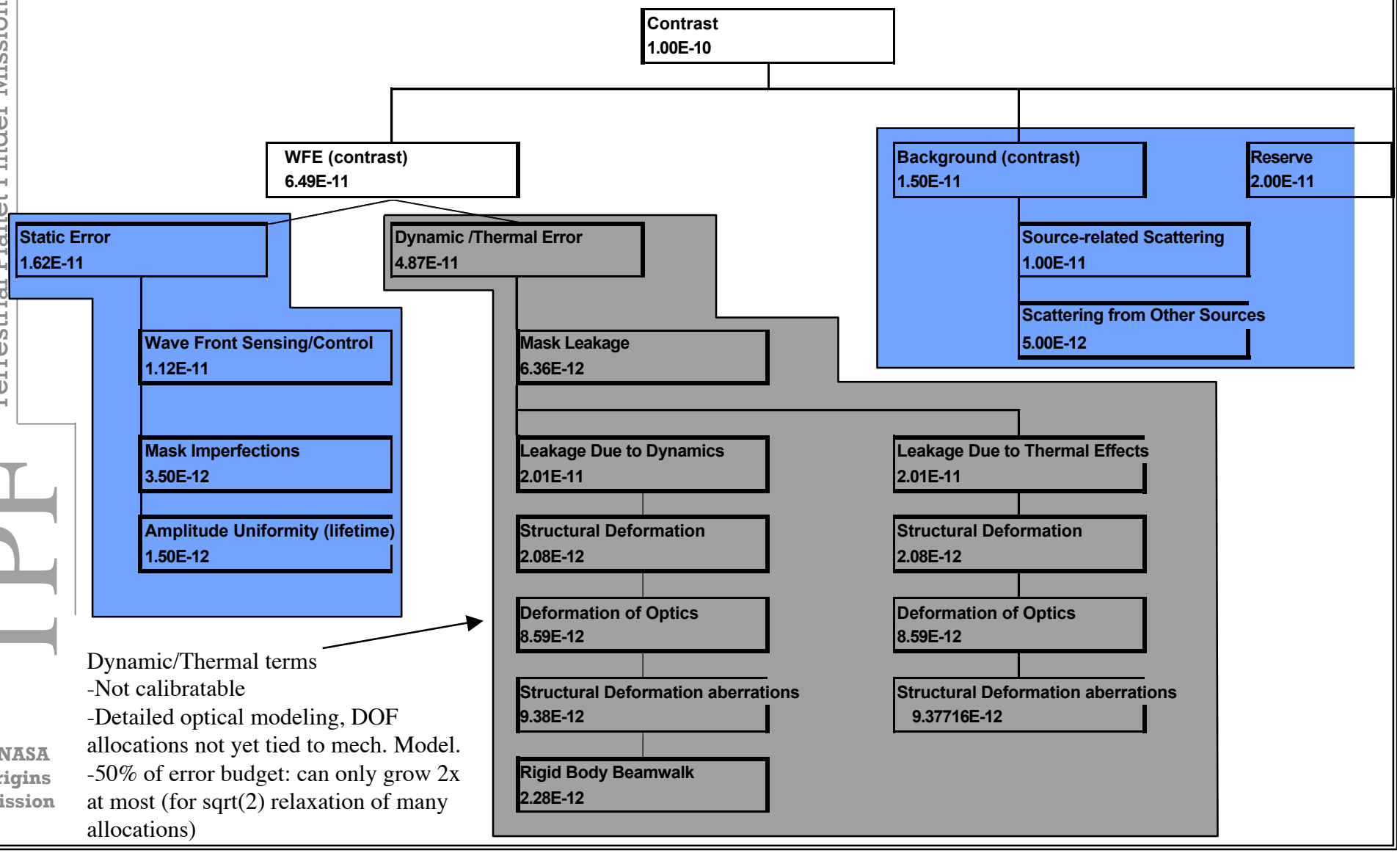
TPF Coronagraph Error Tree: 3??D



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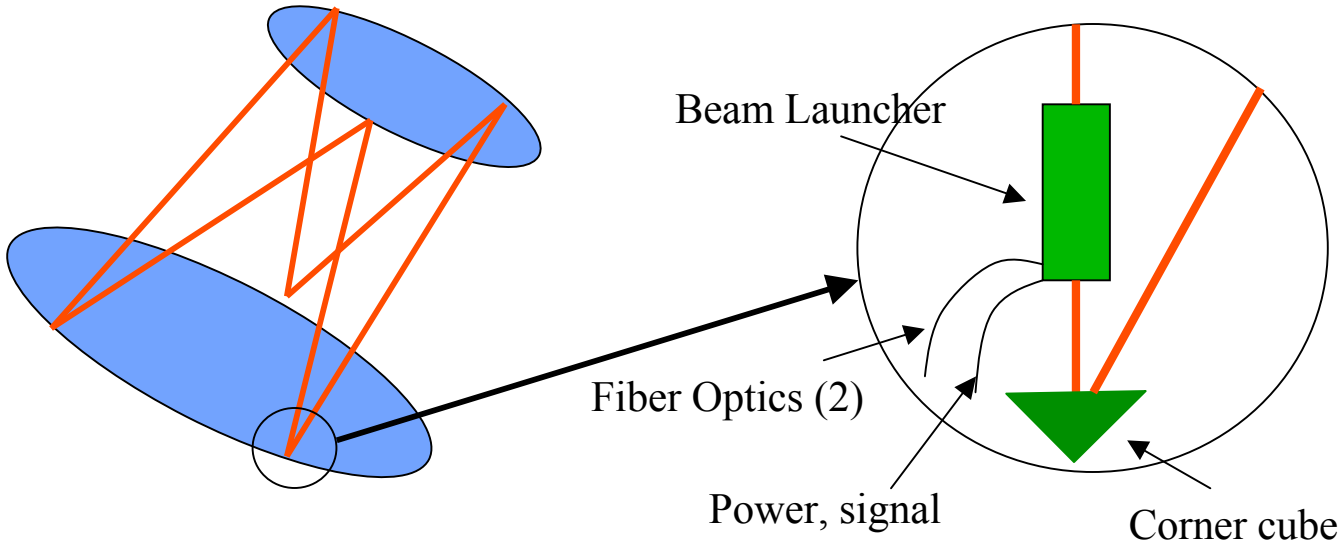
Dynamic/Thermal terms
-Not calibratable
-Detailed optical modeling, DOF allocations not yet tied to mech. Model.
-50% of error budget: can only grow 2x at most (for sqrt(2) relaxation of many allocations)

Error Budget Comments

- Modeling of Thermal/Dynamics shows some surprises
  - Aberrations, not beam walk, limit the allowed motion of optics
    - Assumes optics with lambda/140 – lambda/180 surface figure, f^{-3} power spectrum
    - Super-quality optics not required (but I've ignored folding of high-spatial frequency errors into dark hole)
  - Primary-secondary relative motion is very tight: few nm
  - Allowed motion of small optics is 100 nrad and 50 nm
  - Beam walk is relatively flat from 2-4 lambda/D
  - Aberrations are heavily weighted at 2 vs 3 lambda/D
  - Aberration stability is specified in picometers for low-order Zernike terms (focus, astigmatism, coma). (Note: 1 A = 100 pm).
  - Radial band-limited masks are insensitive to astigmatism and trefoil
  - Visible-nuller equivalent mask is insensitive to focus.
    - sin(x)*sin(y) mask requires pi phase elements
- Micrometeoroids and particle contamination may be limiting factors to (static) background
  - But what is coherent vs. incoherent component of the scattering?

Laser Truss for TPF Coronagraph

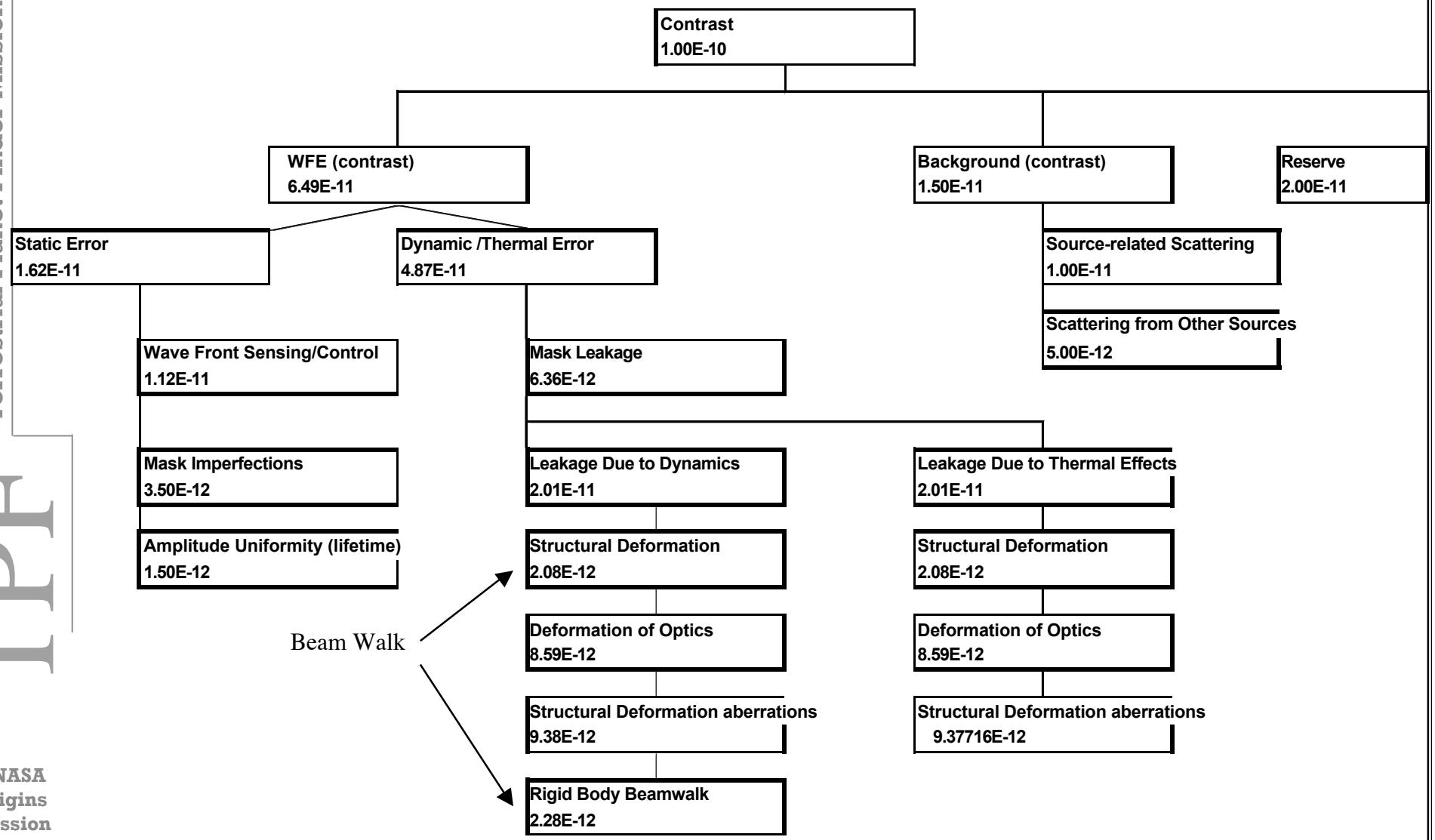


Six metrology beams form an optical truss with ~1 nm resolution.
In addition to the identified components, a stabilized NPRO laser (wavelength=1.3 um), a heterodyne frequency modulation system, and fiber distribution system are used. The laser and modulation system feed the beam launchers from a remote location on the s/c.

Corner cubes must be attached around the perimeter of the optics so as not to obscure the beam. They are required to maintain sub-nm piston (normal to optical surfaces) stability during observations.

For short design, we get ~ factor of 2 more precision with 1.6x more precise metrology.

TPF Coronagraph Error Tree: 3??D



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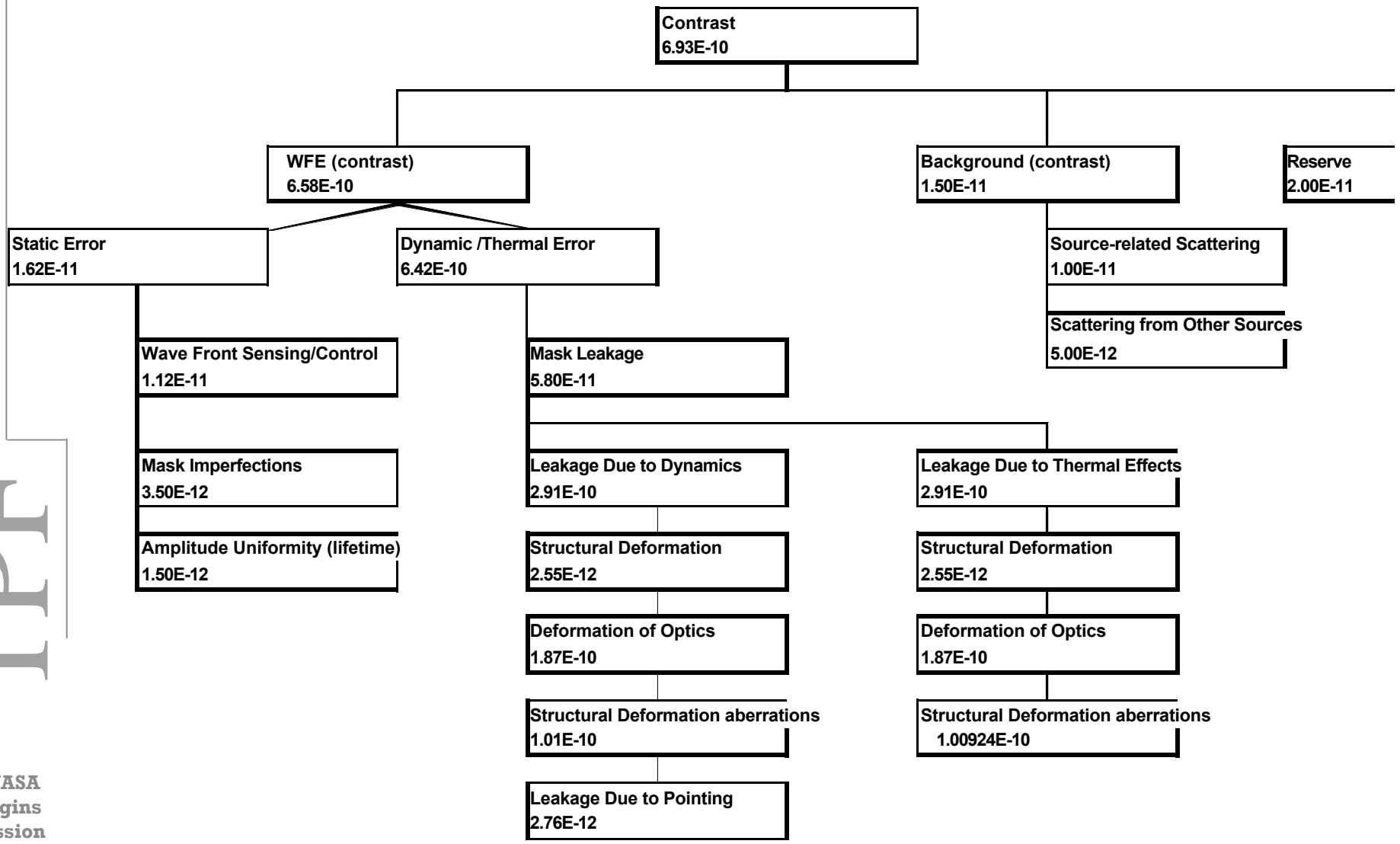
TPF Coronagraph Error Tree: 2??D



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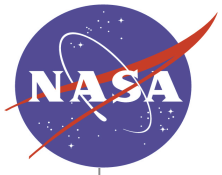
2 vs. 3 λ/D (1 of 2)

How hard is planet detection at 2 vs 3 cycles?

Criteria	2 vs 3 cycles
Wave front Sensing	Same
Stray light	Same
Amplitude Uniformity	Same
Mask Performance	~Same
Beam Walk Sensitivity	~Same
Pointing	2x tighter at 2 cycles
Integration time	*2-3x longer at 2 cycles*
Aberation Sensitivity	*3-4 x higher at 2 cycles*

Static performance is about the same: the wave front can be set for 2 lambda/D as readily as at 3 lambda/D.

Dynamic/Thermal performance is the distinguishing characteristic. Stability requirement is 10 times tougher at 2 cycles. (See next page.)



Summary

- Coronagraph performance is driven by sensitivity to changes in low-order aberrations.
  - Very sensitivity at 3 lambda/D
  - A larger telescope operating at 4 lambda/D is less sensitive to changes in aberrations and has shorter integration times (win both ways)
  - But larger apertures are obviously more expensive, harder to test, and make almost everything besides the aberration sensitivity more challenging.
- There are many mitigating factors that have not been included in the error budget:
  - Differential imaging (roll about line of sight and difference the images).
  - Spectral speckle smearing
  - Calibration, e.g. temperatures have some correlation to aberrations
- There was not time in this brief presentation to discuss progress in
  - Stray light analysis
  - Micrometeoroid damage predictions
  - Mask amplitude and phase sensitivity
- Future direction: 8 m vs 6 m, and full mission design.